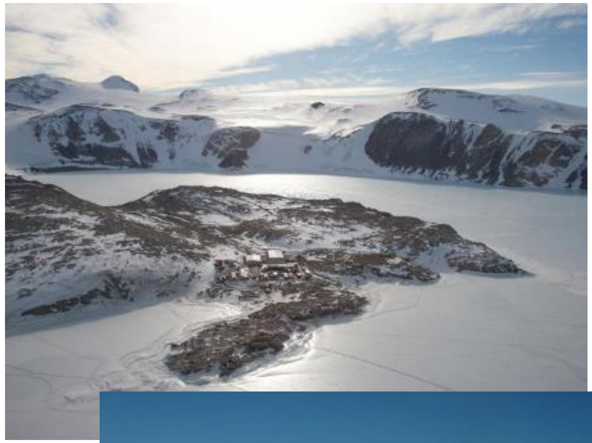

Performance assessment of the LoMiRad ultra-wideband low frequency radiometer

Ada Vittoria Bosisio, Marco Brogioni, Alessandro Lapini, Massimo Baldi, Francesco Montomoli, Joel T. Johnson, Giovanni Macelloni

Consiglio Nazionale delle Ricerche
The Ohio State University
Agenzia Spaziale Italiana

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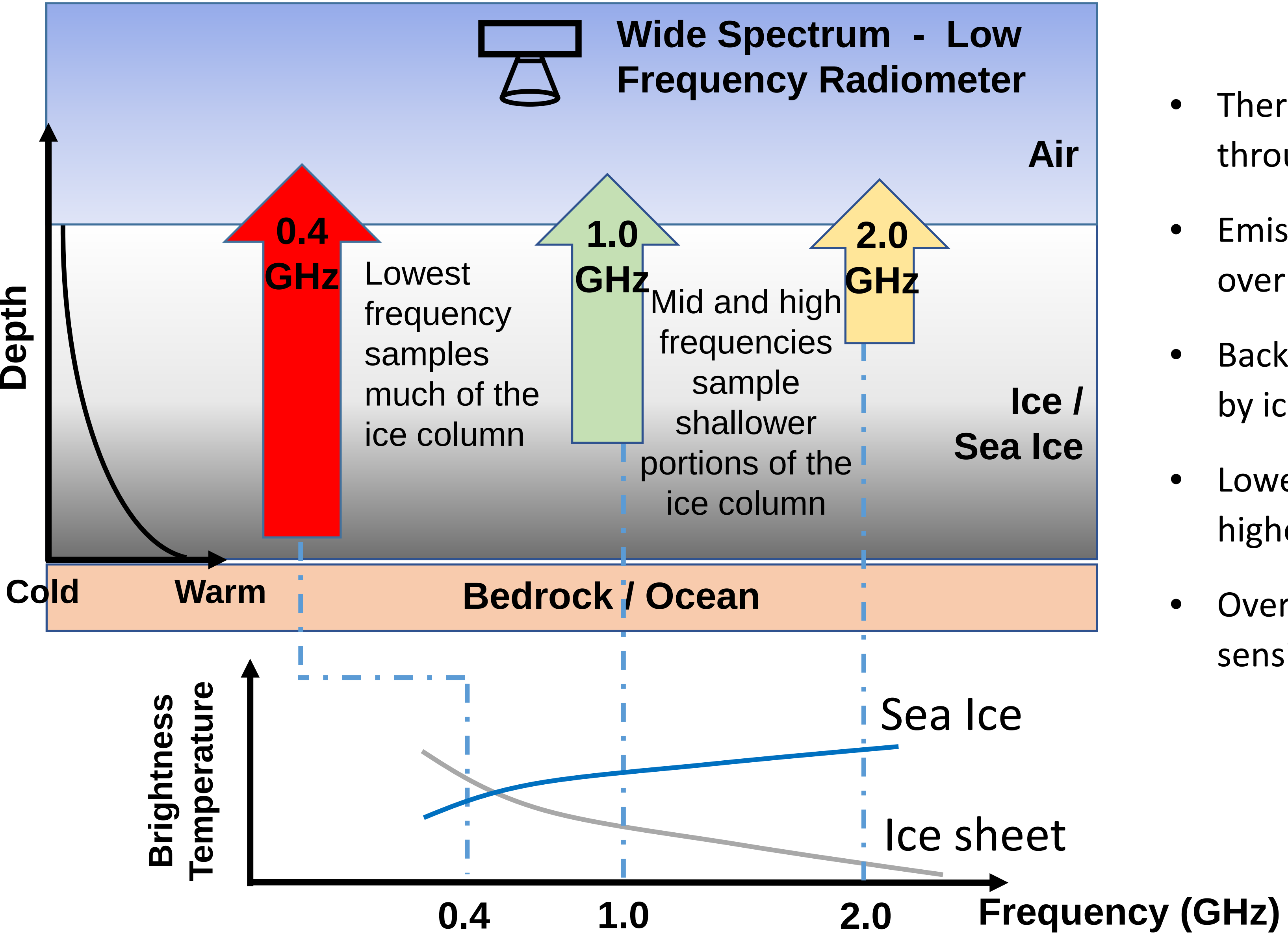
Introduction

- CNR and OSU have been active in microwave radiometry for many years, working on modeling, data analysis, experimental campaigns, and instrument design.
- in the 2014, OSU introduced a new approach for Earth remote sensing: ultra-wideband low-frequency microwave radiometry (or better: spectroscopy)
- The approach samples the microwave spectrum continuously from 500-2000 MHz and uses these 'wideband' brightness temperature data to retrieve properties of the surface
- The UWBRAD project, coordinated by OSU in collaboration of many US and EU scientists, developed an airborne radiometer and performed modeling studies to demonstrate potential in the field. The primary targets of interest were sea ice and ice sheets.
- Continuous spectral sampling allows for:
    - RFI detection and mitigation
    - optimal use of the spectrum to improve sensitivity (i.e. NEdT)
    - use of spectral trends in geophysical parameter retrievals

How to measure – the physical basis



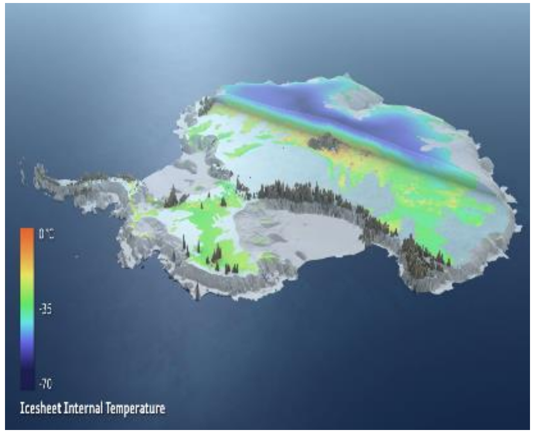
- Thermal noise emissions are produced throughout ice sheets /sea ice
- Emission from a given depth is attenuated by overlying ice sheet / sea ice
- Background emission (ocean/rock) is attenuated by ice sheet / sea ice
- Lower frequencies observe greater depths, higher frequencies shallower
- Over ocean, lower frequencies are more sensitive to sea surface salinity

Introduction

- Spaceborne deployment of the concept has been considered both by NASA (PolarRad concept) and ESA (CryoRad, Earth Explorer 10, 11 and 12). CryoRad approved for ESA EE-12 phase 0 study in 2024.
- The Italian Space Agency further supported the preparation of the Earth Explorer proposal with two dedicated studies:
  - ASI Cryorad in 2015
  - ASI Cryorad Follow-On in 2020
- One of the **aims** of the latter was the **development of an airborne European UWB radiometer** to
  - support the development of the new technique
  - foster new campaign opportunities in the US and EU
  - support national industries

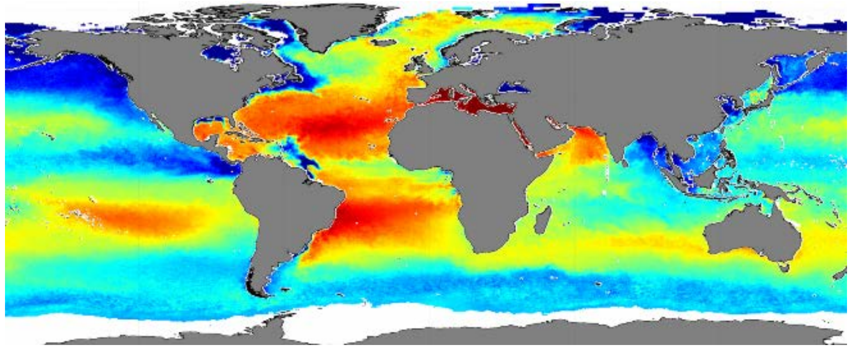
ESA EE12 Cryorad mission

MO1: Improving understanding of the processes controlling the mass balance and stability of ice sheets and ice shelves, their current and future contributions to rates of global sea-level rise



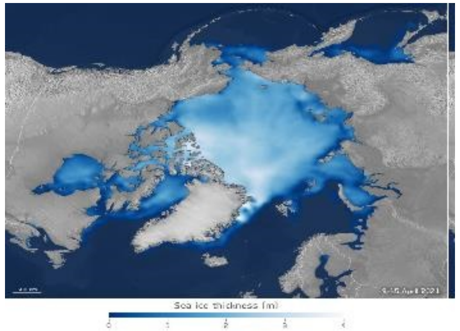
- **Ice sheet and ice shelf temperature profiles**;
- **Presence of intraglacial water** (i.e. aquifers) and **water at the bottom** of ice sheets (i.e. basal melt)

MO2: Bridge the observation gap for sea surface salinity in cold waters to provide new insights into the freshwater cycle and water mass formation at high latitudes



- **Sea surface salinity** with special focus on high latitudes where there is high uncertainty

MO3: Monitoring sea ice growth and salinity exchange processes in the Arctic and Antarctic



- **Sea Ice Thickness** in the range 0-2 m
- **Sea Ice Salinity** in the range 0 - 20 g/kg not presently available from space
- Relative **error expected ≈ 10%**

LoMiRad requirements

The main requirements of the radiometer were:

Main RF Specification

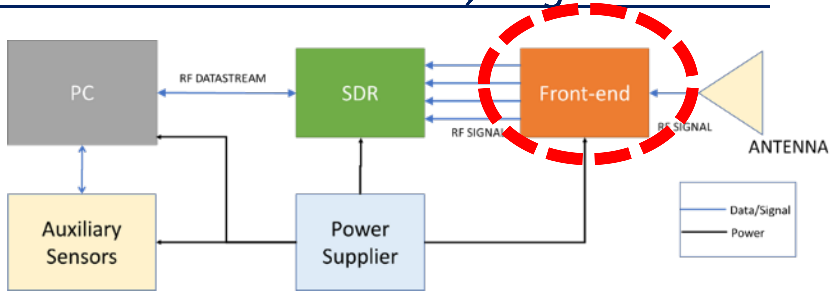
Concept	Wideband spectral-Radiometer
Frequency	0.4 – 2 GHz continuous
Polarization	Circular
Incidence Angle	Nadir
Input channels	1 (mandatory), 2 (preferred)
Reference loads	2 (mandatory), 4 (preferred)
Output channels	16
Radiometric Res.	< 0.5 K
Absolute Accuracy	< 1 K

Main Operational Specification

Parameter	Value
Weight	<50 kg, to be lifted by 3 people
Operational temp.	-40°C ÷ +40°C
Platform	Airborne, ground and truck deployment
Power supply	24 ÷ 28 Vdc, (110/320 Vac optional)
Max power abs	1 kW
Case	19” standard rack

- Implemented the total power radiometer configuration
- Built using connectorized devices instead of smd components (ease of characterization, each device can be substituted easily without major impact on performance even during a campaign).
- direct conversion scheme, avoiding analog mixers and local oscillators (and their relative issues like temperature dependence)

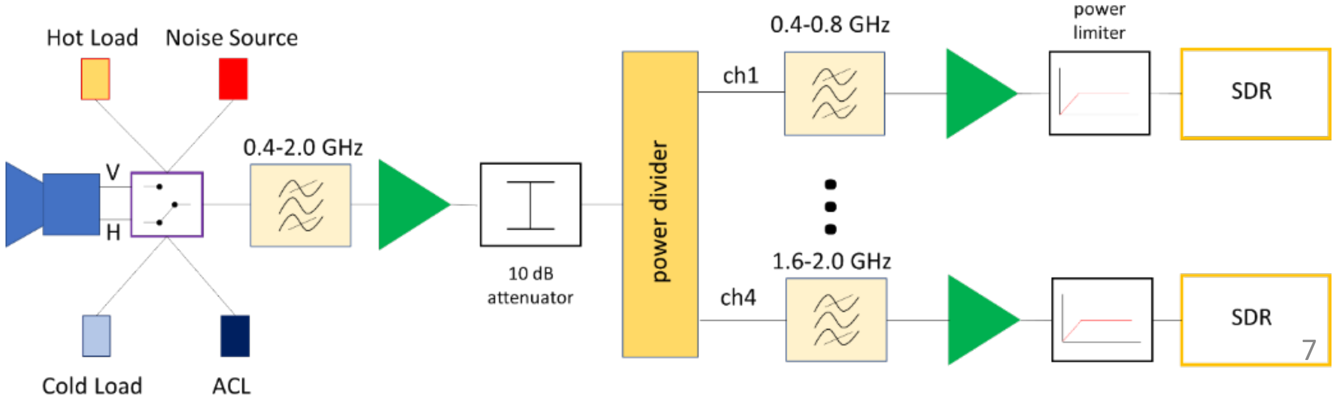
LoMiRad front-end

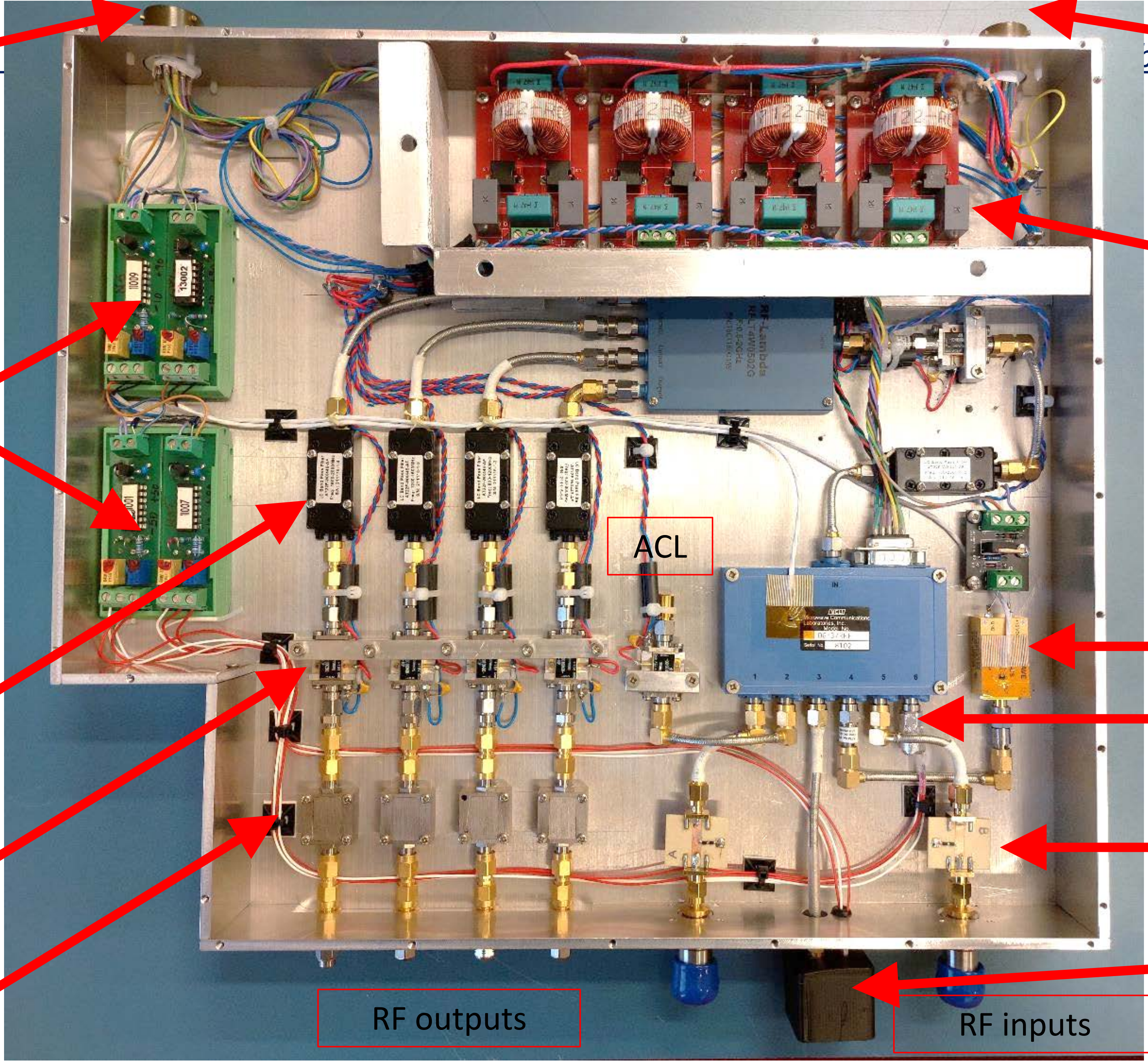


Characteristics of the front-end inputs:

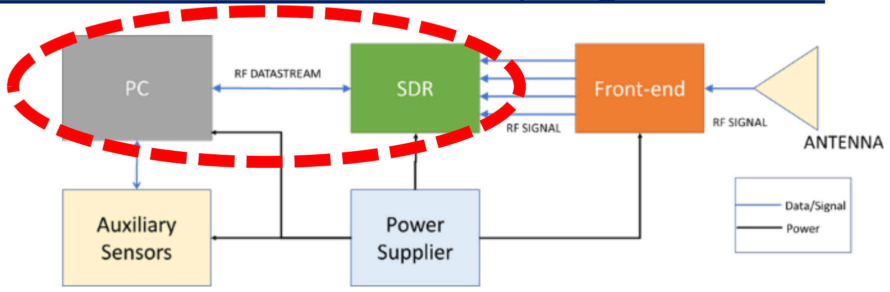
- two input ports for a dual pol antenna
- Active Cold Load – ACL, same LNA as used in the front end. Eq. temp ~ 130 - 190K dep on frequency
- Cold load, termination at ambient temperature incorporated in a copper block. Temp ~ 290K,
- Hot load, termination inside of the RF front-end at about 330K . Front-end temperature is controlled through a PID device
- Noise source that can be switched on/off. Represents a target at about 400-450 K.

- Preferred to use devices produced by known companies as much as possible
- The following components were selected for the RF section.
  - •MCLI D6-3/REF SP6T microwave pin-diode switch,
  - •Narda-Miteq LNA-40-00100400-13-10P,
  - •RF LAMBDA RFLT4W0502G 4-way power divider,
  - •AAREN Technologies cavity filters,
  - •APC AT13A-GX114-AF – limiters

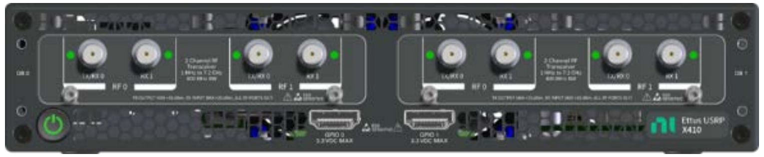



Analog signals output connector
Power connector
Power supply filters (LNAs, mw sw, NS)
PT100 Tx modules (mw sw, NS, Hot and Cold loads)
ACL
NS
subchannel filters
Hot load
2nd stage LNAs
ESD protection
Cold load
Power limiters
RF outputs
RF inputs

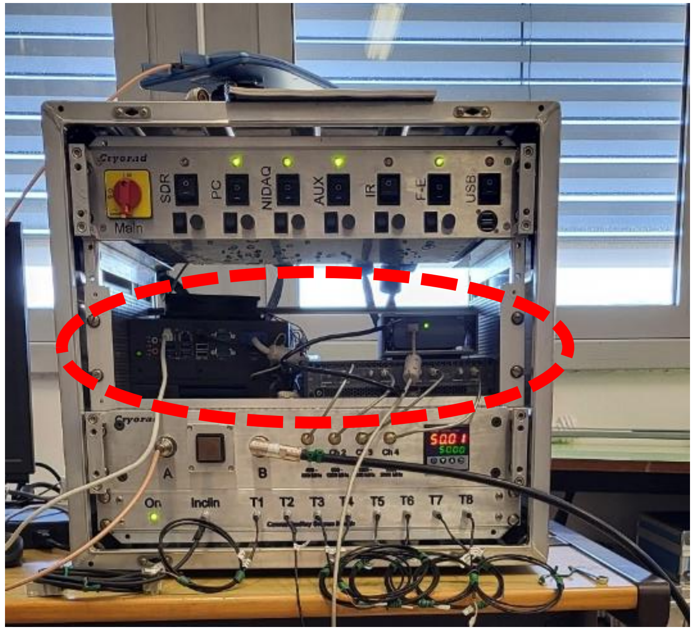
LoMiRad back-end



- The back-end is implemented through an Ettus x410 SDR coupled to an industrial PC.
- Ettus x410 has 4 independent input channels with 400MHz bandwidth each
- Signal is digitized with a 12 bits ADC (15 bit after DDC)



- Processing of the signal in the 4 ch is executed in parallel on the FPGA
- <u>the SDR output data are similar to those of UWBRAD (full-band power and kurtosis @ 400 MHz, sub-band power and kurtosis).</u>
- <u>FFT is performed at 4096 points over a bandwidth of 500 MHz (122 KHz spectral resolution)</u>
- <u>single spectrogram is ~ 1 sec long with granules of ~ 1 ms</u>
- All the DSP is coded in VHDL under the RFNoC framework
- PC host communicates with the SDR via a 100 Gbit Eth to receive and save data, acquire analog data (temperatures and platform attitude), schedule the acquisition sequence, and perform offline RFI processing



RFI algorithms

The following RFI mitigation algorithms are implemented (in post-processing):

- *Full-band kurtosis*. For each channel, a time bin *x* is considered affected by RFI if

$$|K_{FB}(x) - K_{FB\ no\ RFI}| > K_{FB\ threshold}$$

- *Sub-band kurtosis*. For each spectrogram, a frequency bin *y* is considered affected by RFI if

$$|K_{SB}(y) - K_{SB\ no\ RFI}| > K_{SB\ threshold}$$

- Pulse blanking. Given the power spectral density matrix P(f,t), a frequency f' at time bin t' is considered affected by RFI if

$$|P(f',t') - Median_T[P(f,t)]| > PB_{threshold}\ MAD_T[P(f,t)]$$

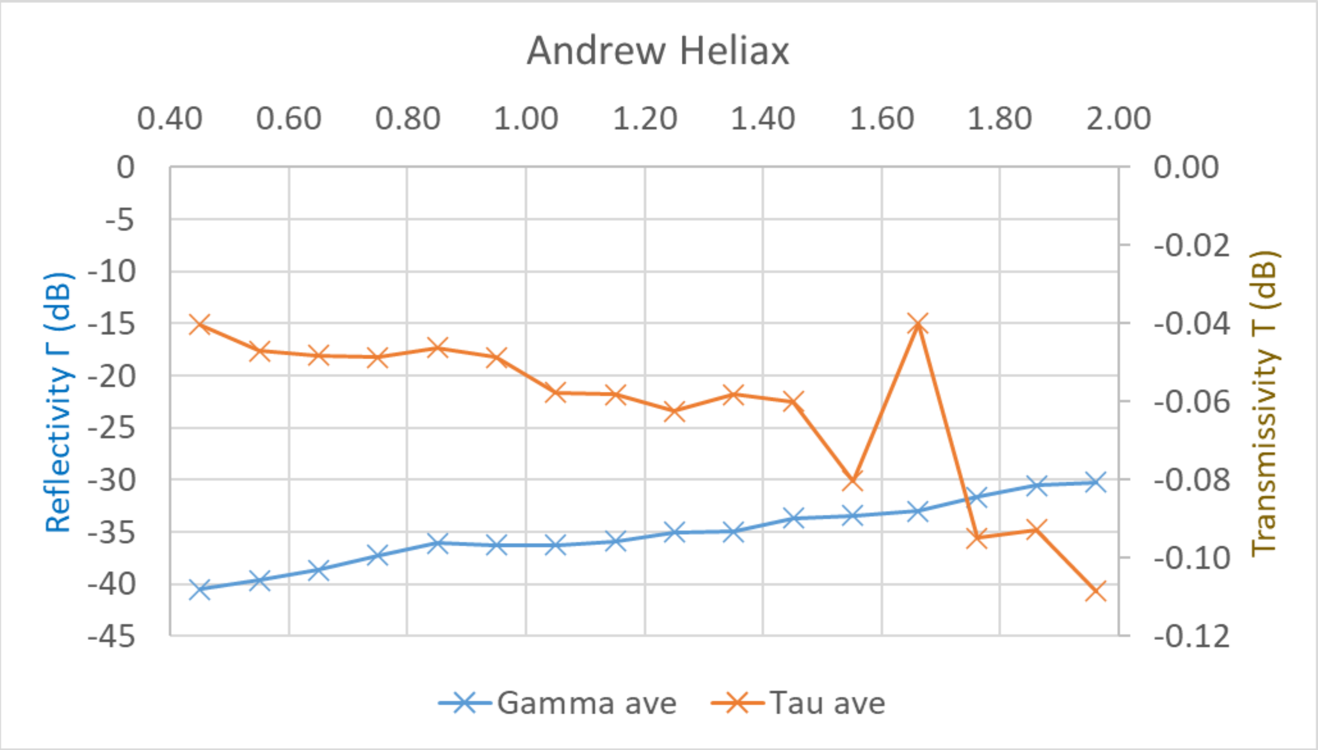
computed in Time for each frequency bin

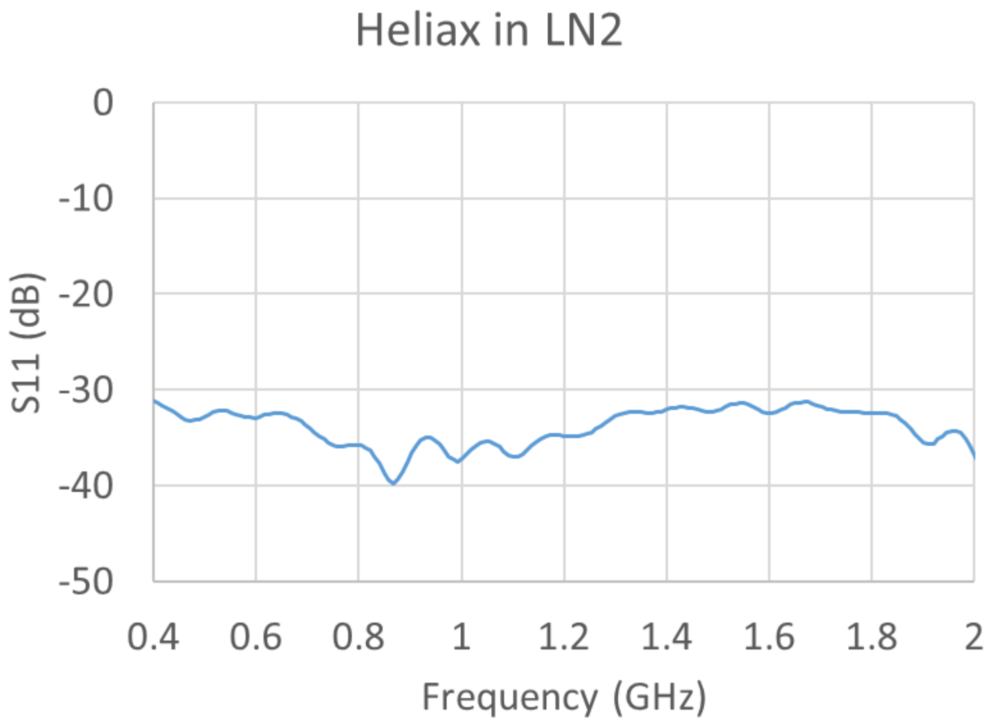
Stability test

- Active Cold Load and Noise Source were characterized in March 2025 with 180 s of data (LN2 & termination at 323K)
  - Integration time set to 400 ms (from lab meas, tradeoff between accuracy and speed)
- Stability test performed in April 2025
  - We collected 2 hours of data on LN2 target for each input port
  - The other input port was terminated with a matched load through a similar cable as for LN2
- Secondary aim: assess the self-RFI presence and its level (if any)

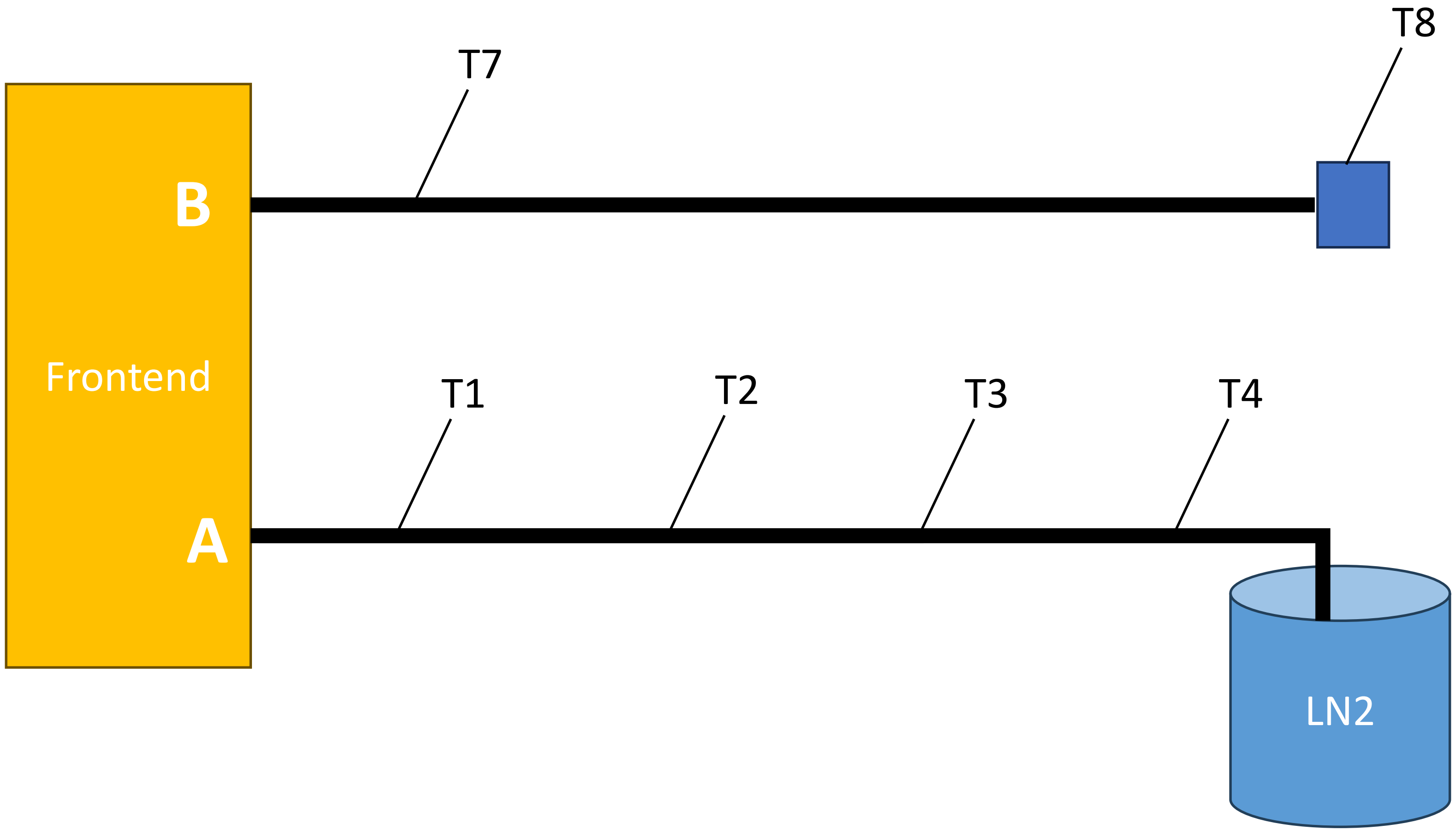
Cables

- We used Andrew Heliax ½" cable (FXL-540 TBC) made of a low density foam with an attenuation of 4.4-10 dB/100m
- We assembled two 1m long cables



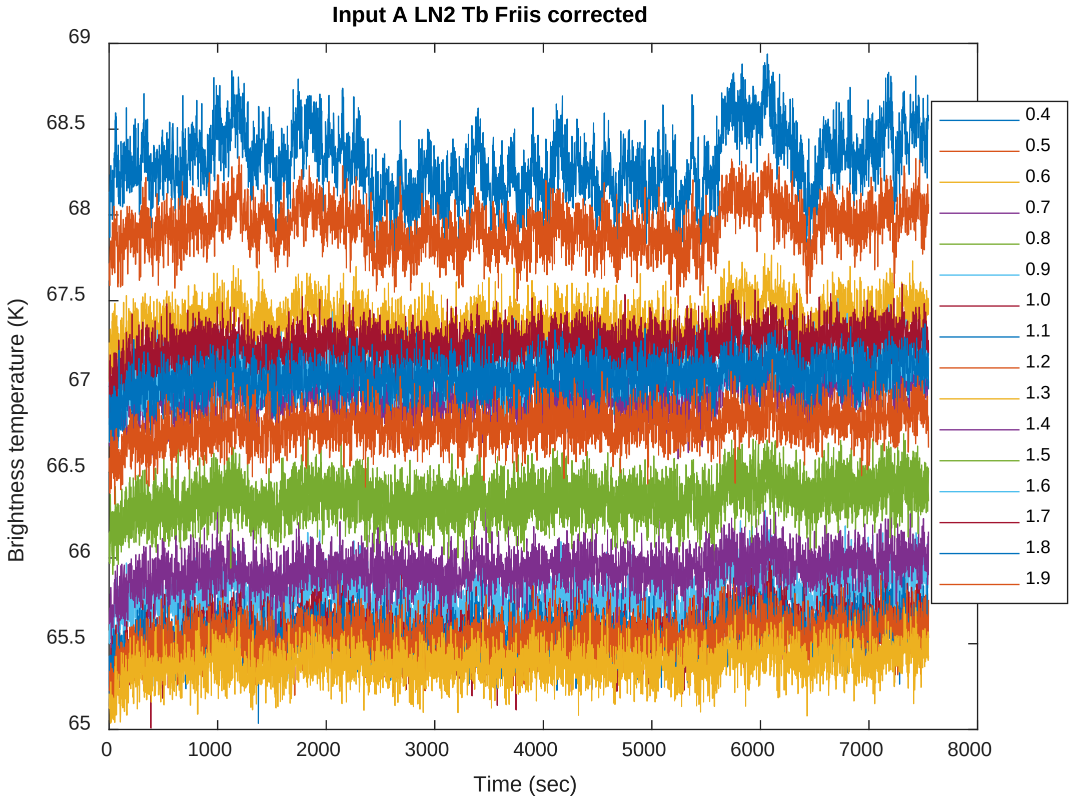


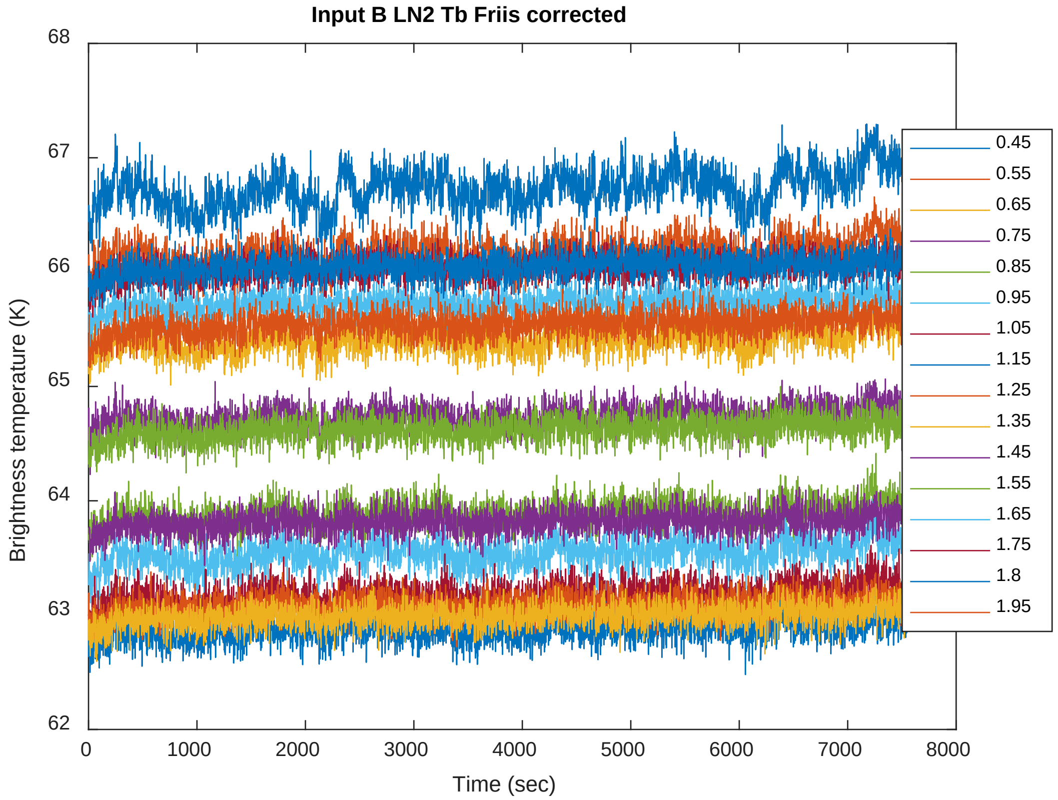
Setup of measurements



Heliax cables (same length) also prevent heat propagation from frontend (50°C) to cables

Results of stability test: 120min LN2

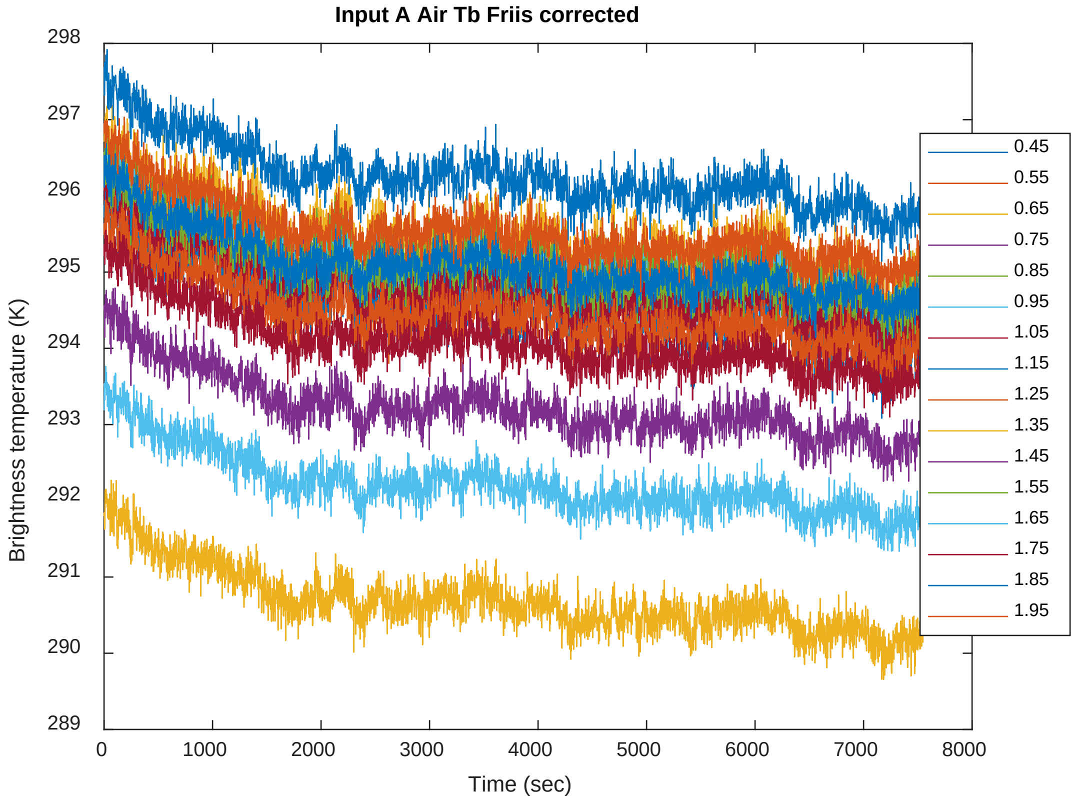


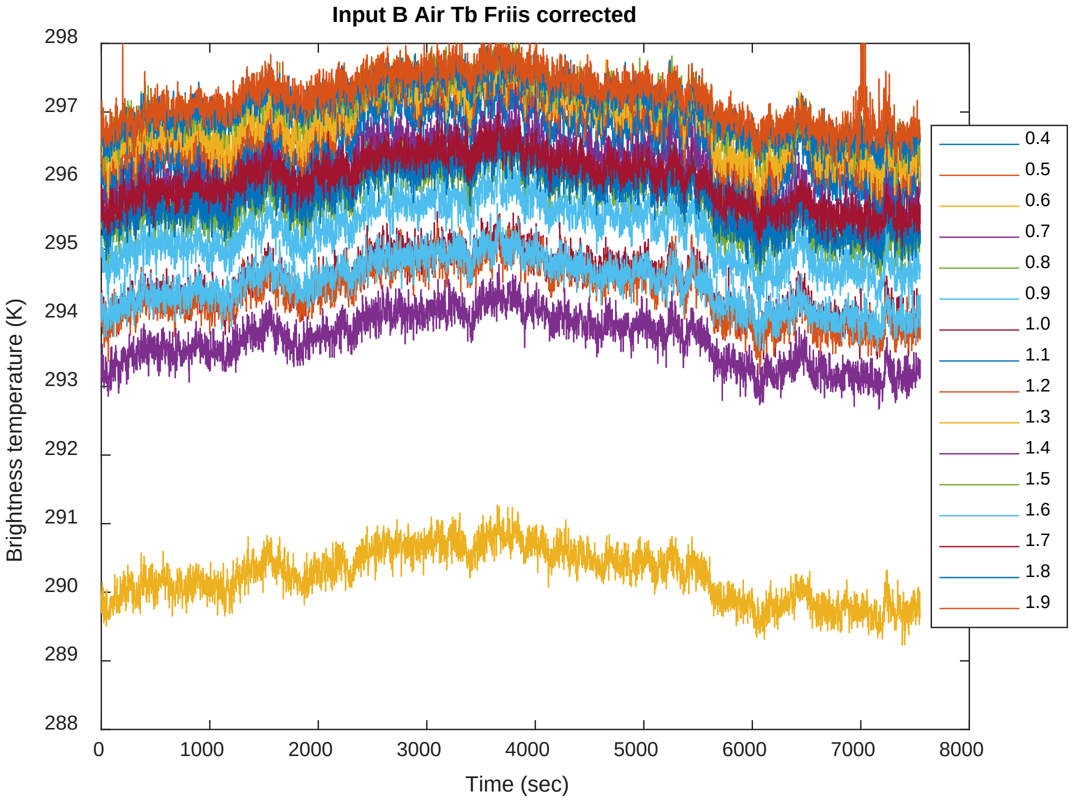


- Variations over frequency: (A) 3.5K Vs (B) 4K
- Average difference: (A) is 2.5K higher than (B)
- Likely due to differences in the mw sw channels (and maybe in the .141 short cables)

no abs calibration!

Results of stability test: 120min air

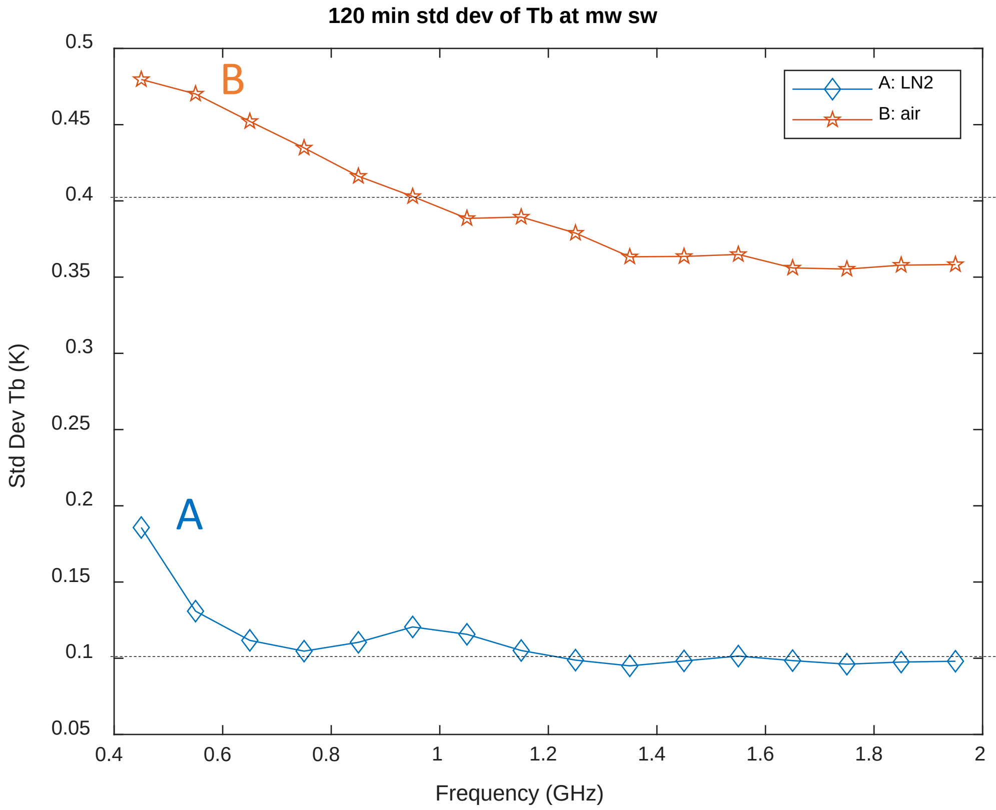


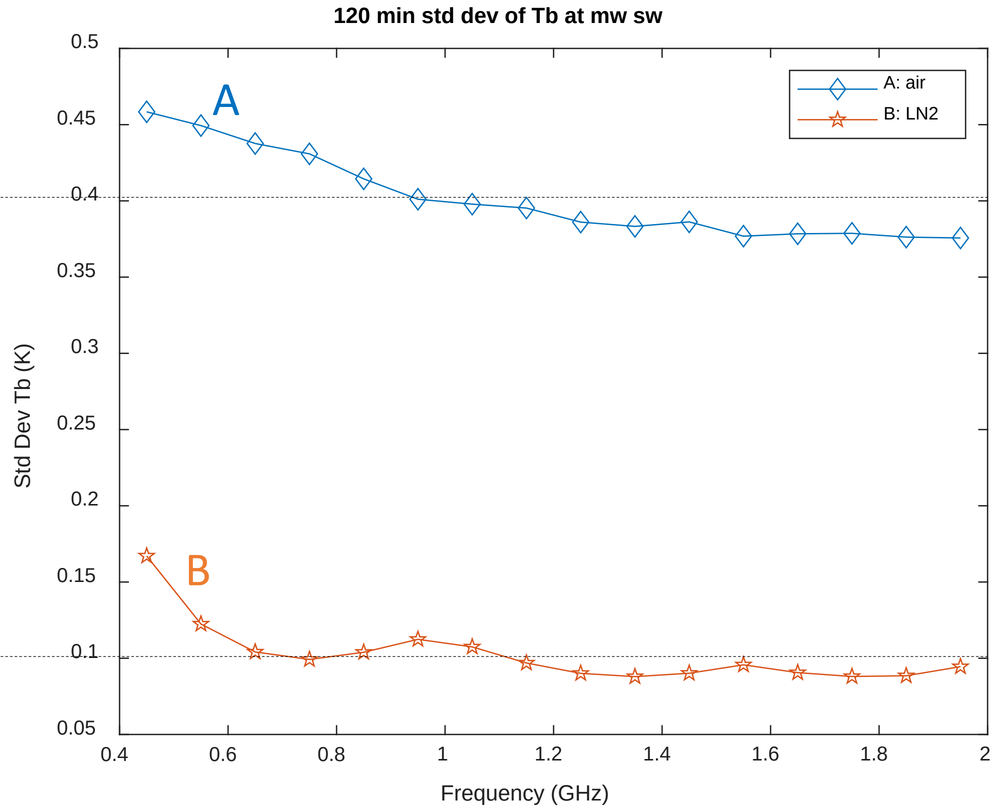


- Acquired in different moments, (A) at night (B) in the morning, with the window of the lab partially open for security concerns (LN2 was evaporating)
- Cal curve developed with Input A measurements
- 1.35 GHz channel need to be better calibrated, all of the others are in the same range

no abs calibration!

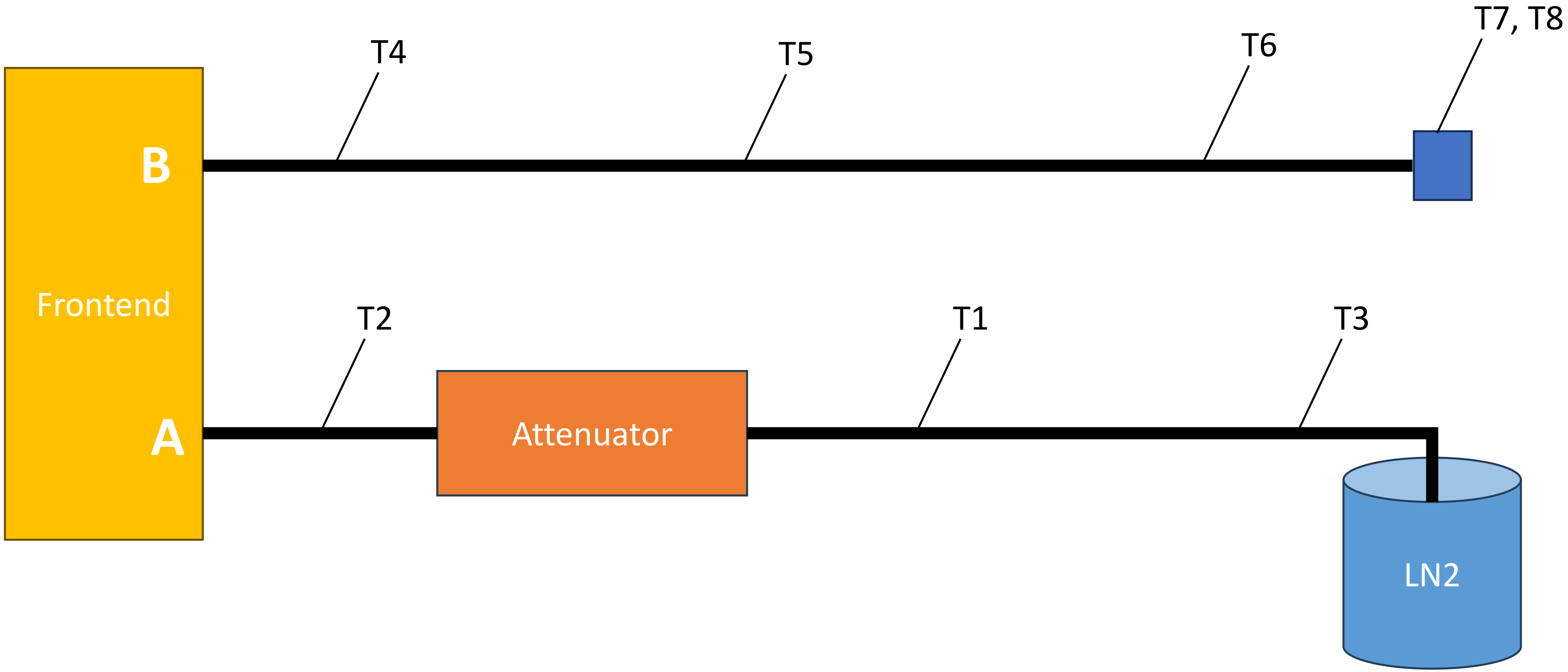
Results of stability test: precision





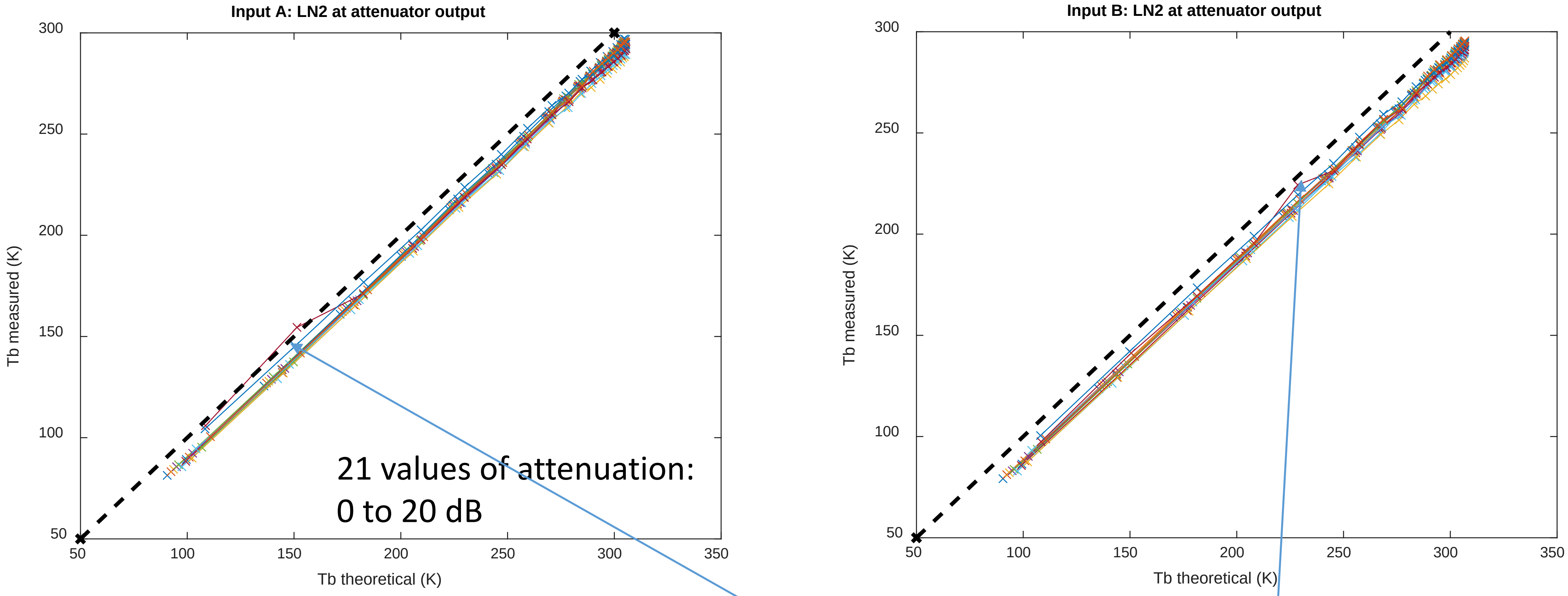
- Both input channels show similar precision
- Precision slightly degrades at lowest channel (likely due to Ettus x410 performances)
- Air datasets not detrended, part of std dev is due to ambient temperature changes

Setup of linearity measurements



Same cables as before, plus a 30 cm cable connecting Input A to attenuator

Results of linearity with raw data

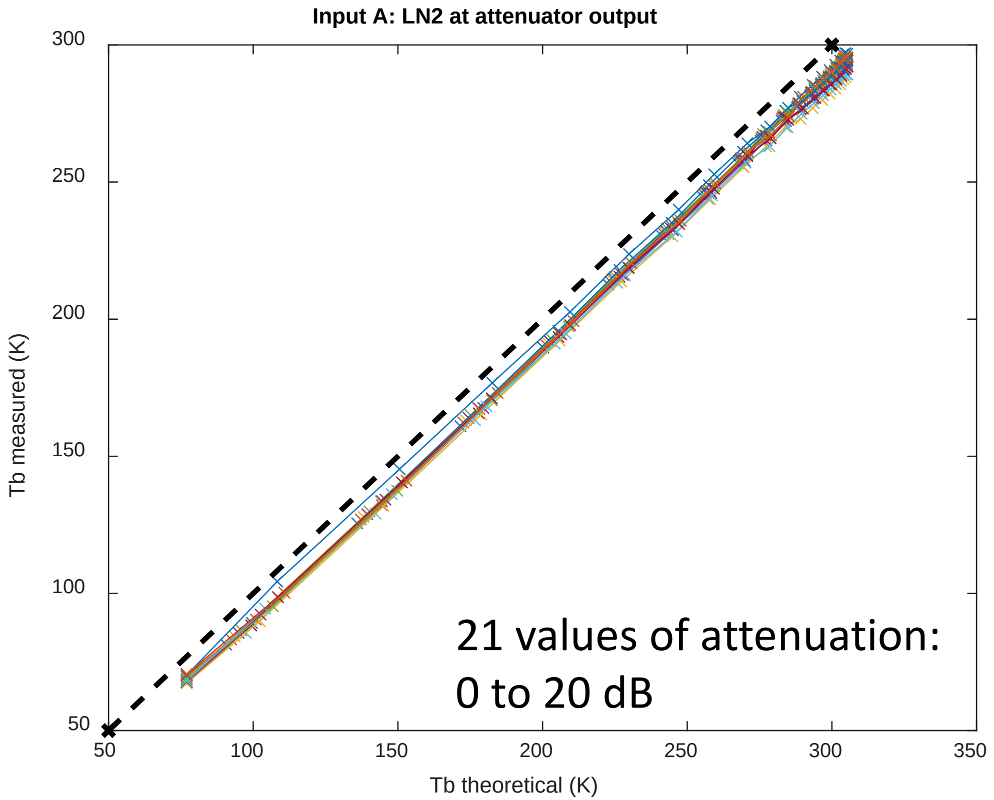


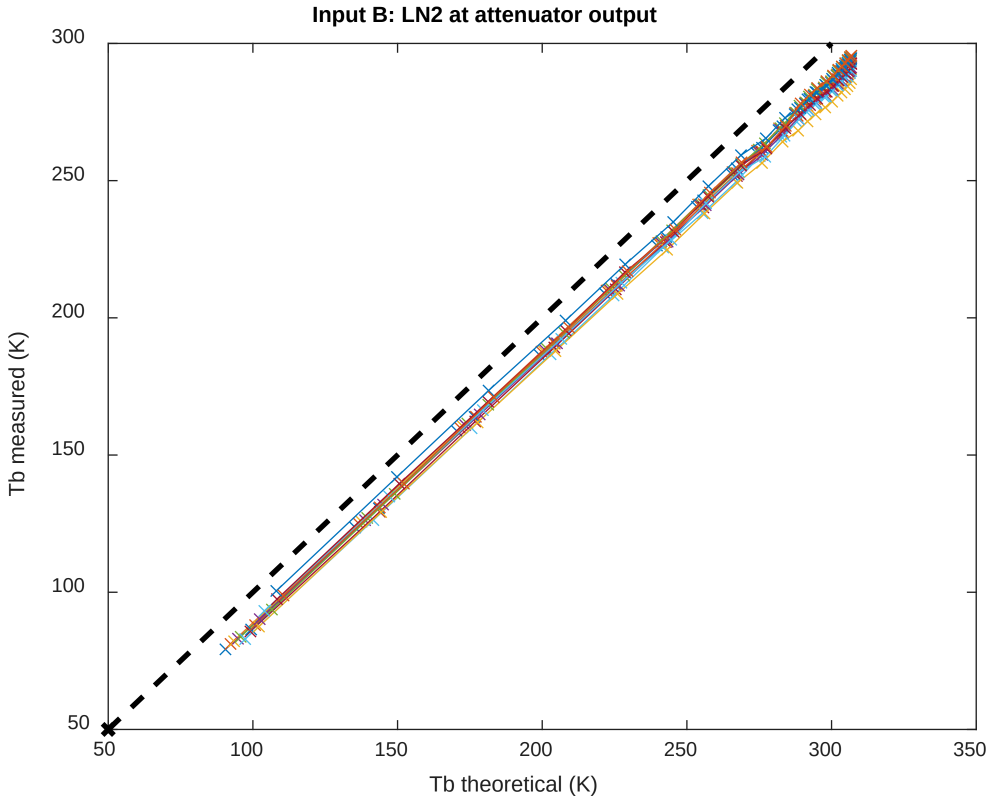
21 values of attenuation:
0 to 20 dB

Anomalous behaviors!

Anomalous behaviors due to a cable connector that loosened (problem of Heliax connectors)

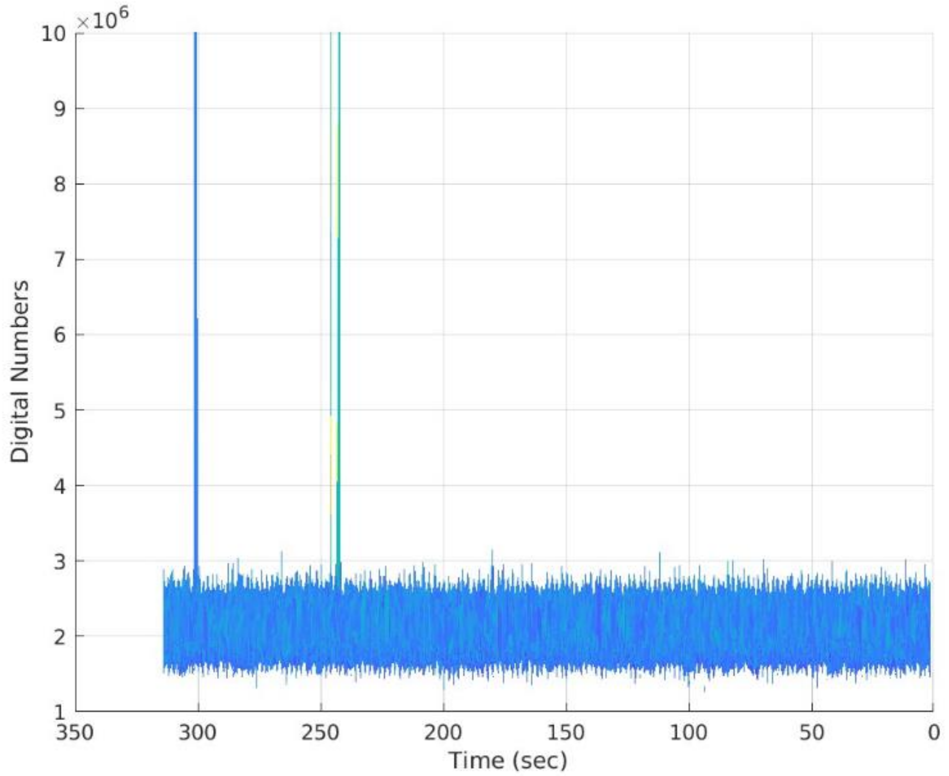
Results of linearity with RFI-mitigated data (PB)



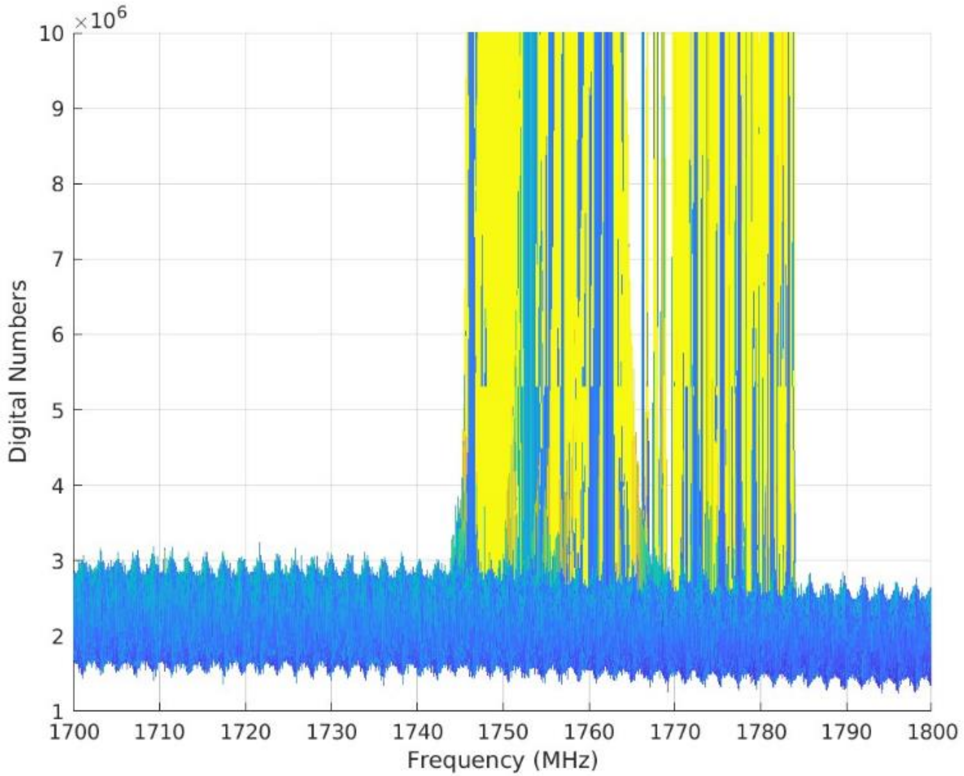


Linearity confirmed over the operative range 77-300K, R2>0.99

Example of RFI mitigated by power blanking



very limited in time



likely due to mobile phone

- 2D plots of 3D spectrogram
- spectrogram at full spectral resolution and 100 ms temporal res.

LoMiRad status

- LoMiRad has been successfully designed and manufactured
- Mechanical, electrical (<350W max) and environmental (49kg) req. have been met.
- Integration time set to 400ms (aircraft platform motion 35 m at 150 Kn)
- RFI algorithms (max power, kurtosis, cross-frequency) implemented, thresholds set but still under refinement
- stability assessed. Precision of 0.1-0.15 K on cold targets (LN2, water), ~ 0.4K on warm targets (e.g. soil) depending on frequency
- linearity assessed $R2>0.99$
- Compensation of antenna/frontend mismatch undergoing (according to Corbella et al., 2005)
- LoMiRad will be deployed in the $CryoS^4$ campaign at Baffin Bay this August.